NEW TECHNIQUES IN MEASURING PLASTIC STRAIN IN A MEMORY MATERIAL

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Watervliet, New York

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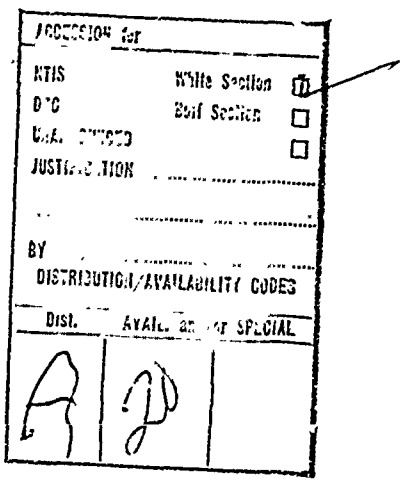

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NEW TECHNIQUES IN MEASURING PLASTIC STRAIN IN A MEMORY MATERIAL

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ABSTRACT

A Nickel-Titanium memory material was studied for the purpose of characterizing its stress-strain behavior, energy absorption capacity, and cyclic response. Instrumentation problems encountered in the testing of this unique material are discussed from the standpoint of thermal recovery effects on strain readings from strain gages and LVDT-type extensometers. Nickel foil type temperature sensors were used to measure surface temperatures from heat generated in the course of plastically straining the material. In addition, the sensors also monitored the heat applied to the specimen to effect thermal recovery from the plastic strain. Temperature-time curves using a strip chart recorder exhibited possible phase changes occurring in the material during thermal recovery after the half cycle of straining.

INTRODUCTION

The intermetallic compound NiTi has received considerable attention from researchers[1] because of its unusual shape-memory property. The generic name for this compound is 55 Nitinol, so called because of its being developed[2] at the Naval Ordnance Laboratory. The behavior which makes this material unique is that the material may be strained into the plastic region, unloaded, and then given a thermal recovery treatment which enables it to recover from all or most of the permanent strain. Usually the material is "set" in the memory configuration by giving it a 900°F heat treatment while it is constrained in the desired shape. This will usually increase the a ability of the material to recover when subjected to thermal recovery treatments involving temperatures around 200°F or less. Figure 1 illustrates the behavior for a specimen tested in tension, unloaded, and given a thermal treatment to effect recovery.

Because of the thermal recovery aspects of the material, several interesting problems became evident in instrumenting the specimens to obtain meaningful, repetitive, stress-strain data. These problems and our approach to their solution is the subject of this paper

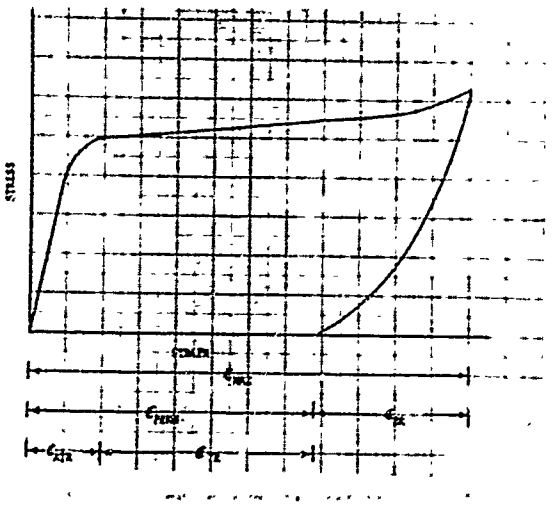
Superior numbers refer to similarly-numbered references at the end of this paper.

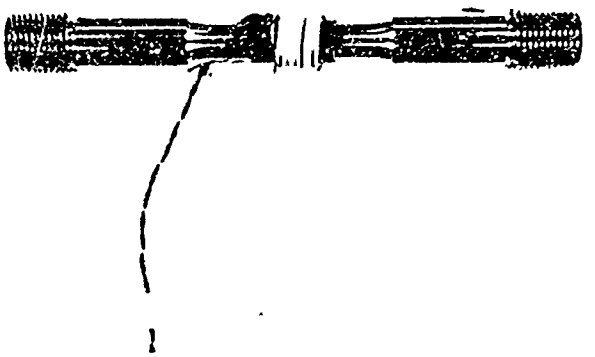
1. Material and Methods of Strain Measurement

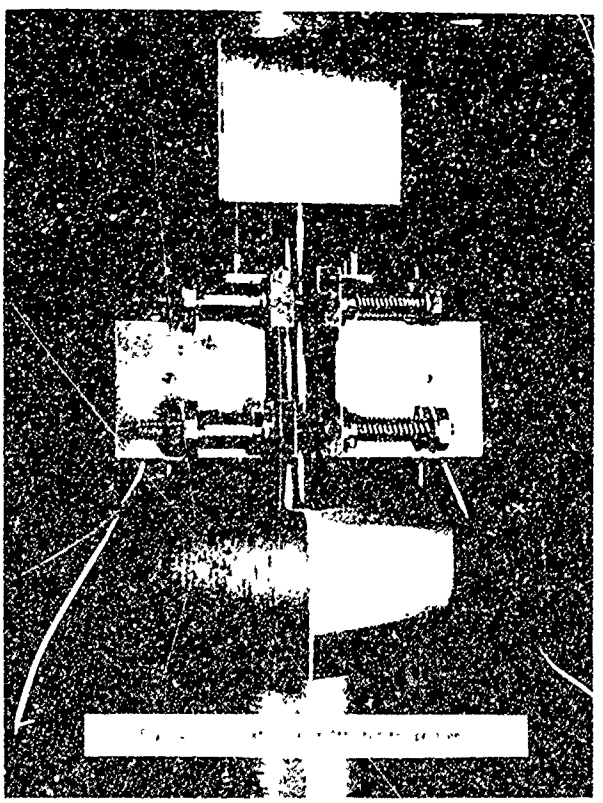
The NiTi alloys were fabricated into 1/2 inch diameter rods by the vendor. These were machined into standard ASTM .357 inch diameter specimens with extended shoulder length to facilitate gripping in the testing machine. Figure 2 shows the specimen configuration. Strains were measured with strain gages and a precision LVDT-type extensometer which has two LVDT type coils that average the strain in one plane. In addition, the upper portion can separate from the bottom portion of the instrument should the specimen prematurely fracture without damage to the extensometer. Figure 3 shows the extensometer attached to a specimen.

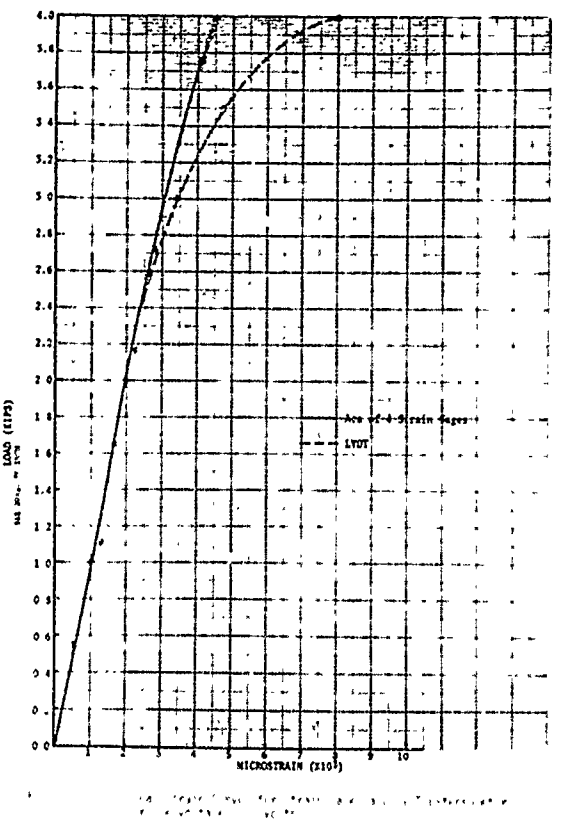
2. Comparison of Strains Measured with the LVDT Extensometer and Strain Gages

As a check on the extensometer instrumentation, wire resistance strain gages were mounted at the quarter points on the circumference of the specimen. The strain readings were averaged and compared with the output of the extensometer. Strain gage reading were obtained using strain gage bridge signal conditioning units and a digital scanning recorder. Figure 4 shows the readings of the strain gages compared with the extensometer. In this case the bridge voltage was 10 volts and the amplification on the digital scanner was 100. Figure 5 shows the same thing except the bridge voltage was reduced to 1 volt and amplification increased to 1000. This shows much better agreement between the strain gage readings and the extensometer. The reason for the discrepancy is due to the dissipation of heat in the material directly under the gage. This causes the material to recover locally near the gage but does not significantly affect the overall behavior of the material for the one inch gage length which is being monitored by the extensometer. At first it was thought that the discrepancy was due to creep resulting from a faulty adhesive, so several lots of adhesive were checked out. These gave the same results. The problem cleared up only when the bridge voltage was reduced to a low value. The classic analogy is the use of strain gages to measure strains for an organic plastic (polymer) material. In this case, steady current techniques may cause a heat buildup sufficient to change the stiffness of the material. Pulse current techniques have been used to obviate this problem and would probably be feasible for Nitinol.








LVDT
MICROSTRAIN (X10³)

3. Thermal Sensors and their Use

Surface temperatures of the specimens were measured using Nickel-foil sensors. Since the grid and backing is very thin, the flexibility is comparable to that of a strain gage. This allows the sensor to conform to the small radius of curvature of the specimen. The sensitivity of the nickel to strain was checked by mounting the gage in both the longitudinal and transverse direction. This was found to be negligible and therefore was neglected. For repeated application of large strains (up to 6 percent in this study) the adhesive used to cement the gage on the specimen will breakdown. Therefore, glass tape with a self contained adhesive was used to prevent the sensor from coming loose, hence maintaining contact with the surface.

Another distinct advantage of using this type of sensor as opposed to a thermocouple will be mentioned. This material is very notch sensitive in tension. Placing a thermocouple in a high tensile strain field would most certainly produce a stress concentration leading to premature failure of the specimen.

4. Heating Coil

A heating coil was fabricated from nichrome wire sheathed in braided glass tubing. This was wrapped around the specimen and provided the heat necessary during the thermal recovery cycle. The amount of heat was manually controlled using AC variacs. Power was nominally in the range of 40 watts. Figure 2 shows the heating coil and thermal sensor on the specimen. This arrangement of the coil and sensor permitted the extensometer to span over the top of both the coil and sensor when attached to the specimen. This technique permitted the extensometer to remain attached to the specimen during the conventional straining portion of the cycle as well as during the thermal recovery phase.

5. Measurement of Load, Testing and Recording Equipment.

Loads were measured with a precision (1/4 percent) strain gage load cell. A universal electro-hydraulic servo-controlled testing machine was used to test the specimens. Strain from the LVDT was placed in the feedback loop, of the machine. This made it possible to control the actual strain rate in the elastic and plastic region of the material and to be able to stop the test at a selected value of strain. Figure 6a shows a strip chart recording of strain vs time and indicates how the strain is held constant up to the maximum plastic strain attained. Figure 6b shows a similar strip chart recording of temperature vs time. This indicates the amount of heat given off during the straining of the material. Figure 6c is a plot of Load vs strain made on a standard X Y recorder. All three plots are made simultaneously during the testing of a given specimen.

Figures 6a - 6c will now be used to describe the testing sequence. The specimen is pulled at a constant $\dot{\epsilon}$ shown as OM' in figure 6a. This corresponds to the region OYM on Figure 6c. During the loading, heat is given off and sensed by the thermal sensor as shown by OM" on figure 6b. The specimen is then unloaded manually and recovers in a non-linear manner. This region is shown as M"U" on figure 6b. and MU on figure 6c. The strain remaining at this point is conventionally designated the permanent strain (ϵ_{PERM}). This should be considered only a temporary permanency because of the phenomenon of thermal recovery associated with this material.

At this point in the test one of the nuts which holds the specimen in the loading fixture is unloosened so that the specimen will be completely unrestrained during thermal recovery. The power to the heating coil is turned on, and the heat is immediately picked up by the thermal sensor. This is shown on the T-t curve of figure 6b. The specimen starts to recover as indicated by U'R' of the ϵ - t curve of figure 6a. The strain recovered during this thermal heating cycle is called the thermal recovery strain, denoted ϵ_{TR}. In this case some strain may still remain after recovery. This is denoted by ϵ_{ATR}, subscripts denoting "after thermal recovery".

From figure 1 , we can see the following relationship:

$$\epsilon_{MAX} = \epsilon_{PERM} + \epsilon_{ER}$$

$$\text{where } \epsilon_{PERM} = \epsilon_{TR} + \epsilon_{ATR}$$

Figure 7 is a plot of temperature vs time for a particular alloy which exhibits a phase change during the thermal recovery as noted by the very significant dip in the curve. This shows an advantage of measuring the temperature of the specimen during the thermal recovery.

Figure 8 shows a plot of percent permanent strain recovered vs number of cycles. In this series of tests, the material was cycled to a maximum of 6 percent strain, unloaded, and given a thermal recovery heat treatment after each mechanical strain cycle. The interesting thing about this curve is that even though there is a proclivity for the material to depart from near 100 percent recovery of the first cycle, that after 20 cycles the behavior results in a closed hysteresis loop with 100 percent recovery.

Summary and Conclusions

A technique for measuring plastic strains in a memory material resulting from mechanical straining as well as during the thermal recovery process has been developed. Using flexible nickel-foil sensors, the surface temperatures were monitored during the straining and during subsequent thermal recovery. These temperature sensors also indicate phase changes during recovery for some of the alloys.

One must be extremely careful when using strain gages with this material. The bridge voltage must be kept very low (with a steady current approach) to prevent excessive heat dissipation. This will cause localized recovery under the gages. Very large errors in the strain measurement can occur if precautions are not taken.

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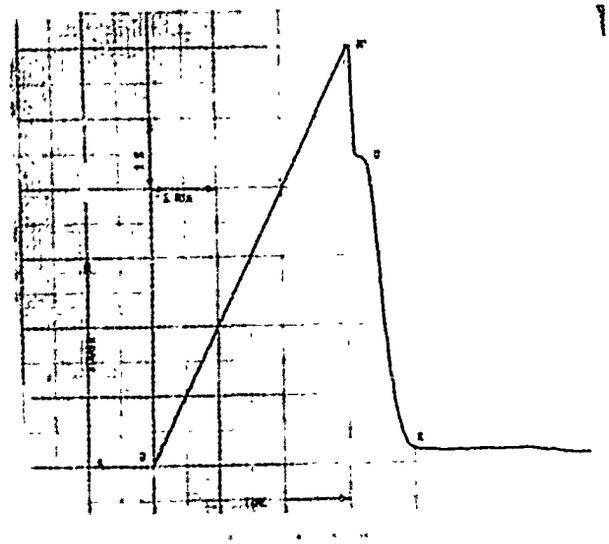
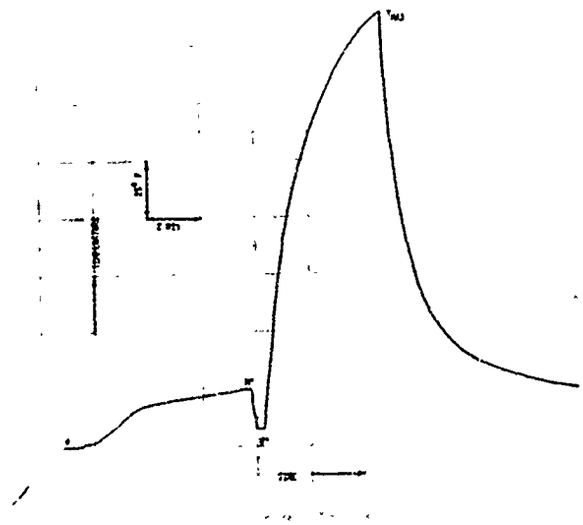
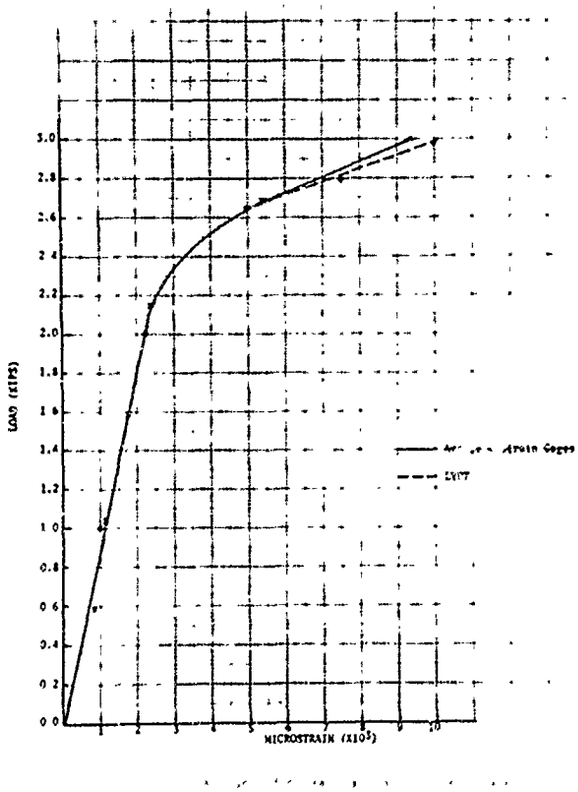
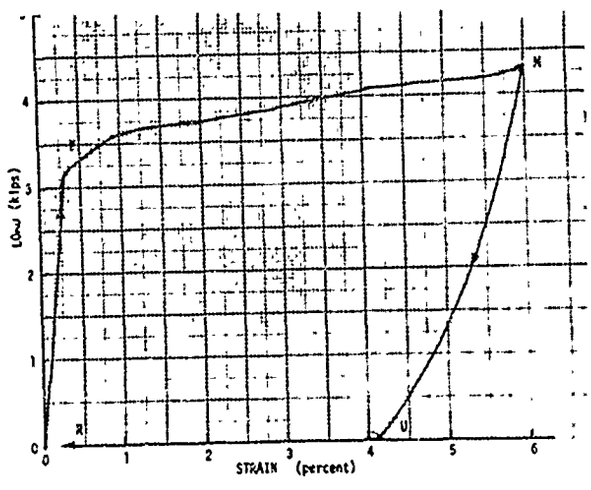
[1]JACKSON, C.M., WAGNER, H.J. AND WASILEWSKI, R.J., 55 *Nitinol - The Alloy with a Memory: Its Physical Metallurgy, Properties and Applications* NASA SP 5110 1972.

[2]BUEHLER, W.J. AND WILEY, R.C., *TiNi-Ductile Intermetallic Compound* Trans of ASM Vol 55 1961 pp 636-639.









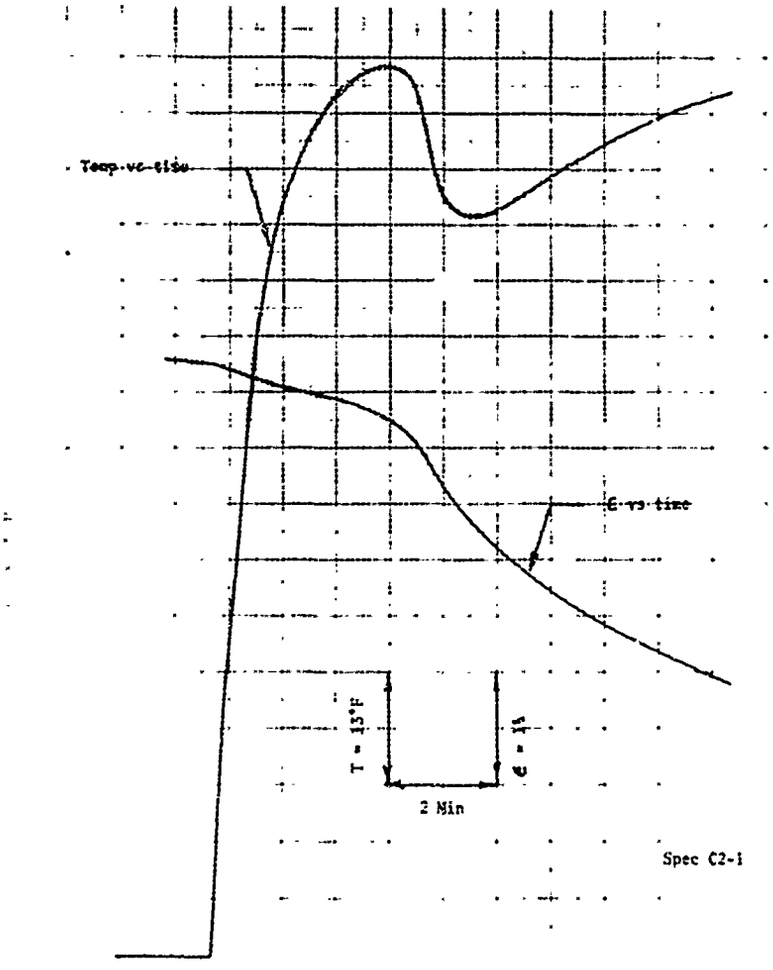


Fig. 7 Temperature-Time Curve Exhibiting a Phase Change During Thermal Recovery

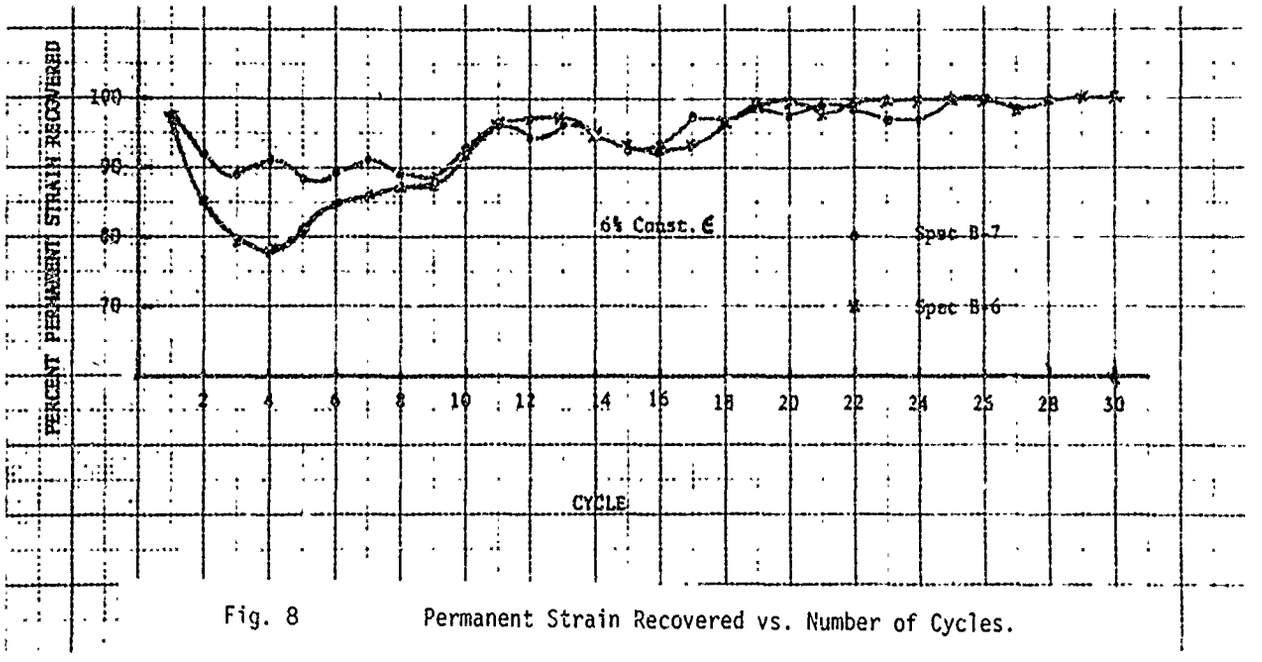


Fig. 8 Permanent Strain Recovered vs. Number of Cycles.